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EFFECT OF TEMPERATURE IN FORMABILITY OF COMPOSITE COMPOSED OF OVERLAPPED FIBRE BUNDLE, THERMOPLASTIC RESIN AND METAL

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Abstract. A structure for a composite of fibre-metal laminate (FML) has been proposed, which is composed of reinforcing fibre bundles, thermoplastic resin as the matrix and metal plates. The reinforcing fibre bundles are discontinuous, and are intentionally overlapped in the longitudinal direction. The resin including fibre bundles was sandwiched between the metal plates. The application concept for the industry is composed of three stages. At the 1st stage, FML is fabricated by lamination of reinforcing fibre bundles, thermoplastic resin and metal plates. At the 2nd stage, FML is formed into the final shape of the product by secondary forming processes, such as stretching or bending under a heated condition which melts the thermo resin. At the 3rd stage, the formed product is expected to have high strength. In the present paper, the effect of heating temperature on the deformation of FML at the 2nd stage was clarified. Firstly, the numerical examination was shown on the effect of overlap length on the fracture mode and the reinforcing mechanism in the proposed FML. Based on the result, the minimum bare length for the overlapped part for the discontinuous fibre bundles was determined so that the tensile strength might be as high as that with FMLs with continuous fibre bundles at the 3rd stage. Finally actual FML was experimentally fabricated, and subjected to all though the 1st to 3rd stages to verify the efficiency of the FML. In particular, the effect of heating temperature was focused upon to realize the forming process at the 2nd stage.

1 INTRODUCTION

It would be meaningful to develop materials, including composites, which have both high formability in plastic deformation and high strength after forming. It would be important particularly when the material is employed as structural components for vehicles or architecture. The material should have higher formability and lower flow resistance during forming. On the other hand, the material should have high strength once it is formed into its final shape and used as structural components.

Many research trials have been conducted to develop such kinds of materials which have contradictory properties: high formability and high strength. Ultra-fine-grained metal is one of the most popular materials recently. Several new technologies have been proposed and have successfully formed ultra-fine-grained metals [1]. However, formability and tensile strength still have a contradictory tendency, and that is to say that fine-grained metals with higher strength tend to have lower elongation. Bake hardening is an effective method to satisfy the contradictory requirements [2]. Before bake hardening, the metal plate is relatively soft and easily deformed by cold working processes. After the metal plate is formed into its final shape, bake hardening is conducted to strengthen the metal.

Composites are very efficient materials which realise high strength while suppressing total weight [3]. The efficiency has been evaluated in terms of both mechanical properties and formability in the forming processes [4, 5]. However, it is generally difficult to subject the formed composite to secondary forming processes which require plastic deformation.

Discontinuous reinforcing fibres are inevitably used for composites to secure secondary deformation. Some composites with short fibres are proposed using an aluminium matrix, and their manufacturing methods are presented [6, 7]. However, short fibres would lead to lower strength than long fibres. "Stampable sheets" which are composed of a net of fibres and a thermoplastic matrix, have been proposed with emphasis on the formability at secondary deformation [8, 9]. "Stampable sheets" would enhance the flexibility in forming under the condition that the deformation is bending and the length is kept constant during the deformation. However, "stampable sheets" would not be applicable for forming processes where the composites are elongated because the fibres are woven into the shape of a net.

Fibre–metal laminates (FMLs) have been developed as hybrid structures, which have the durability of metals with the impressive fatigue and fracture properties of fibre-reinforced composite materials. The mechanical properties of FMLs have been investigated [10, 11]. There are also some research studies focusing upon the blast response of FMLs [12, 13]. Even though the fatigue and fracture properties of FMLs are excellent, the formability of FMLs is not secured.

In the present research, a structure of FML has been proposed for the purpose of maintaining substantial elongation at the secondary forming process as well as providing high strength [14]. The structure is composed of reinforcing fibre bundles, thermoplastic resin as the matrix and metal plates. The reinforcing fibre bundles are discontinuous, and are intentionally overlapped in the longitudinal direction. The resin including fibre bundles was sandwiched between the metal plates. Finite element analyses were carried out for the examination of the structure in terms of stress distribution and composite strength. Based on the analytical results, experiments were carried out to verify the formability in secondary forming under a heated condition as well as the strength after being cooled to room temperature. In particular, the effect of heating temperature was focused upon to realize the forming process at the 2nd stage.

2 INTRODUCTION OF A STRUCTURE FOR FIBRE–METAL LAMINATE (FML)

FML has been proposed by the authors, which is able to be greatly elongated at secondary forming and which provides a high level of strength in one direction after the secondary forming [14]. **Figure 1** shows the application image of the FML and the verification procedure by laboratory experiment. At the 1st stage of the application, FML is formed by lamination of reinforcing fibre bundles, thermoplastic resin and metal plates. At the 2nd stage, FML is formed into the final shape of the product by secondary forming processes, such as stretching or bending under a heated condition which melts the thermo resin. At the 3rd stage, the formed product is expected to have high strength. In the laboratory experiments for verification, FML is firstly formed by lamination into the shape for a tension test. The FML is elongated under a heated condition. After being cooled, the FML is subjected to a tension test for the measurement of mechanical properties.

In the proposed structure, the reinforcing fibre bundles are discontinuous, and are intentionally overlapped in the longitudinal direction. When the overlap length is satisfactorily long, the FML would have enough strength at the 1st stage. If the FML is heated at an appropriately warm temperature to melt the thermoplastic resin, the FML would be elongated with reduction of overlap length at the 2nd stage. If the overlap length is still long, the FML would maintain strength at the 3rd stage.

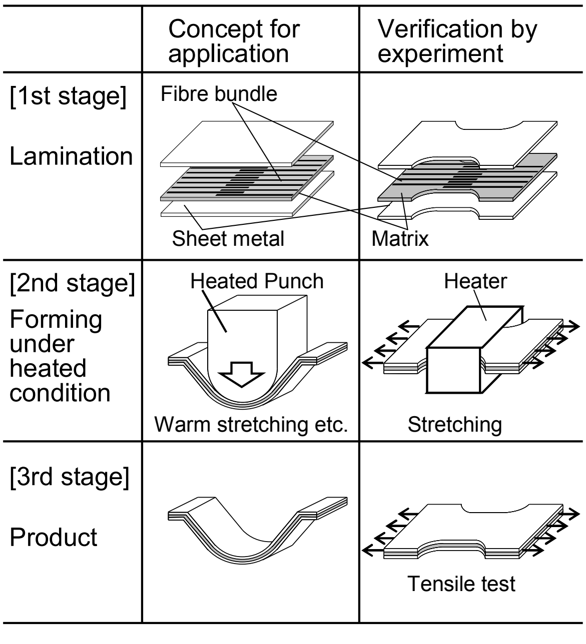


Figure 1: Concept and experimental procedure for FML

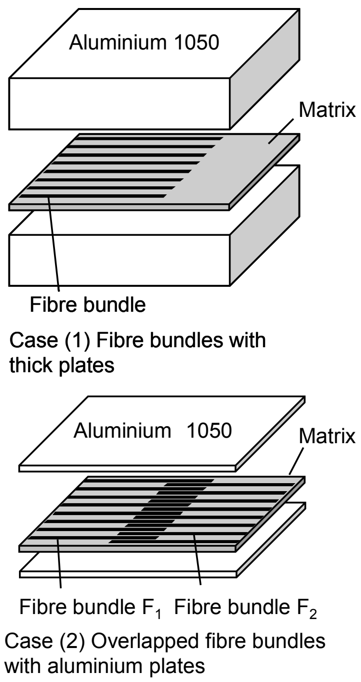


Figure 2: Schematic illustration of composites examined in FE analysis

3 FINITE ELEMENT ANALYSIS OF FML

3.1 FEA model for FML

The unique point of the proposed FML is the existence of overlapped fibre bundles.

Thermoplastic resin around the overlapped fibre bundles is required to withstand certain stress for maintaining the high strength of FML. In order to clarify the role of the overlapped part, a series of analyses was carried out.

Two types of models were adopted for the analyses as shown in **Fig. 2**. The fibre-bundle diameter was fixed at 0.43 mm, which was the same as the actual one used in the experiment. The thickness of the matrix of thermoplastic resin was 0.56 mm, which was determined from the measured value of tentatively formed FML. In the analyses, FMLs are elongated in the parallel direction to the fibre bundles by applying displacement at one of the FML ends.

Fibre bundles and thermoplastic resin are sandwiched by two metal plates of 5 mm thickness in Case (1). While one of the fibre-bundles ends is connected to one end of the FML, the other end is embedded into the resin. As the metal plates are much thicker than the fibre-bundle diameter, the FML is supposed to deform almost homogeneously without being affected by the existence of the fibre bundle. Therefore, Case (1) would simulate the behaviour of fibre bundles and resin in homogeneous deformation, i.e. in idealistic deformation of the composite. Fibre bundles, supplied from two directions, are sandwiched by two metal plates of 0.49 mm thickness in Case (2).

Numerical models in finite element analysis (FEA) are shown in **Fig. 3** taking Case (2) as an example. Elastic-plastic analysis was carried out using the commercial code ELFEN, which was developed by Rockfield Software Limited, Swansea. Implicit scheme was used. Metal plates and thermoplastic resin were treated as elasto-plastic material and fibre bundles were assumed to be elastic material. A von Mises' yield criterion was adopted for elasto-plastic materials, and the normality principle was applied to the flow rule. Constraints were dealt with by the penalty function method. The F-bar method was applied to the hexahedra element for overcoming volumetric locking with simple brick-type elements [15].

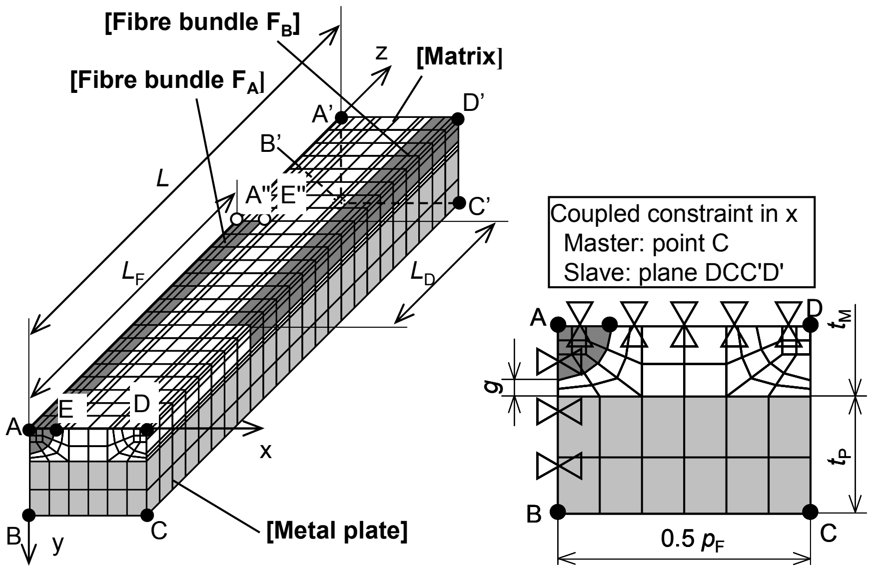


Figure 3: FEM model for composite

As the nodes between different materials belong to both materials, no slippage occurs, i.e. the materials are assumed to stick together completely. A half model was adopted in the thickness direction considering the symmetry. Only two fibres are modelled considering the periodicity in width direction. As the centre axis of fibre would be straight if a number of fibres exist periodically, surface ABB'A' is fixed in x direction as shown in Fig. 3. Although the other surface CDD'C' is not fixed in x direction, the movement of nodes on the surface are coupled so that the displacement of the surface CDD'C' should be the same. While surface A'B'C'D' is fixed in z direction, displacement is given to surface ABCD during tension test.

3.2 Stress distribution during numerical tensile test

A series of analyses was carried out for clarifying the reinforcing mechanism of the proposed FML by comparing stress distribution between different structures. The geometry of FML is shown in **Table 1**. If stress concentrates at some area, the tensile strength would decrease due to localized deformation. As stress concentration would occur at either the fibre bundle or boundaries between the fibre bundle and matrix, axial stress σ_F along the axis of the fibre bundle and shear stress τ_M on the boundary were evaluated. The evaluation lines for σ_F and τ_M are A-A" and E-E", respectively, in Fig. 3.

Table 1: geometry of FML

Total length (L), mm		60
Fibre bundle	Diameter (D_F), mm Length (L_F), mm Overlap length (L_D), mm Pitch (p_F), mm	0.43 28 - 40 (Case 1) 6, 20 (Case 1) 1.0 (Case 2) 1.0 at overlapped part
Matrix	Thickness (t_M), mm	0.56
Plate	(Case 1) Annealed aluminium 1050, thickness t_P=5.0 mm (Case 2) Annealed aluminium 1050, thickness t_P=0.49 mm	

Figure 4 shows the result for Case (1) which would simulate the behaviour of fibre bundles and matrix in homogeneous deformation. With increase of nominal strain ε of the laminate, axial stress σ_F of the fibre increases while the length L_S of the area, where shear stress τ_M is equal to yield shear stress of matrix τ_{My}, expands. At the same time, the length of part L_A, where axial stress σ_F changes at a constant rate at the end of the fibre bundle, also expands. Once nominal strain ε of FML reaches 0.0256, axial stress σ_F reaches rupture level. This phenomenon of stress slope would be explained by the following equation (1).

$$d\left(\frac{\pi}{4}D_F^2\sigma_F\right) = \pi D_F \tau_M dz \qquad (1)$$

where, D_F = Diameter of fibre bundle [mm].

The left-hand side is increase of tension given by axial stress σ_F of the fibre bundle, while the right-hand side is the total force given by shear stress τ_M on the boundary. At the beginning of elongation of the laminate, shear stress τ_M reaches yield shear stress τ_{My} on the boundary at the tip of the fibre bundle. With increase of elongation, the length L_S of τ_{My} expands, and axial stress σ_F has a slope following equation (1) at the end of the fibre bundle embedded in resin. Axial stress σ_F reaches σ_{FP} at the end of the slope and σ_F is constant at σ_{FP} at the plateau area, which is denoted by P_1 for ε=0.012 in Fig. 4. When nominal strain ε is larger than 0.0256, σ_{FP} reaches rupture level. When σ_{FP} reaches rupture level σ_{BF}, the length of axial-stress slope L_C is calculated following equation (2) derived from equation (1).

$$L_C = \frac{D_F \sigma_{BF}}{4\tau_{My}} \tag{2}$$

In the remaining section, let L_C be called critical length.

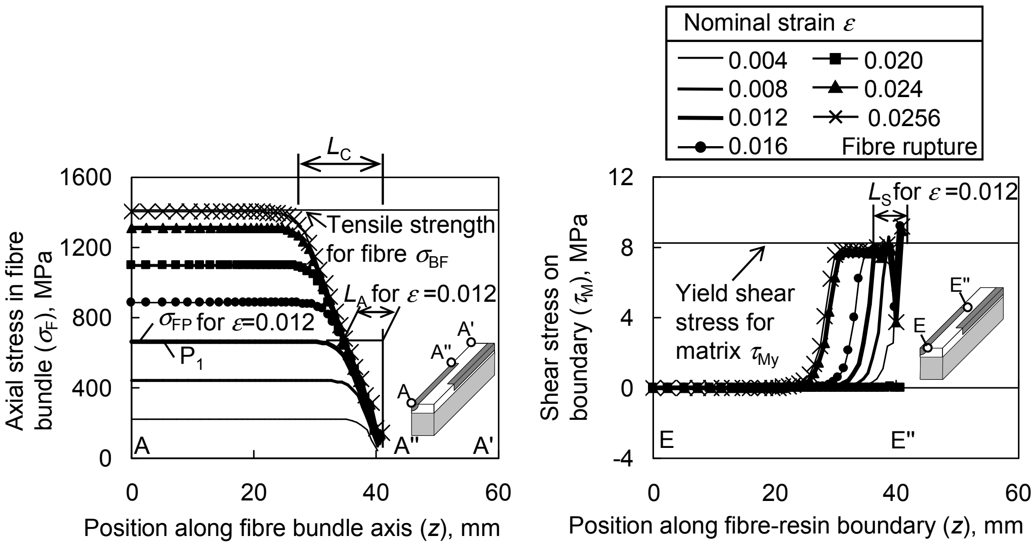
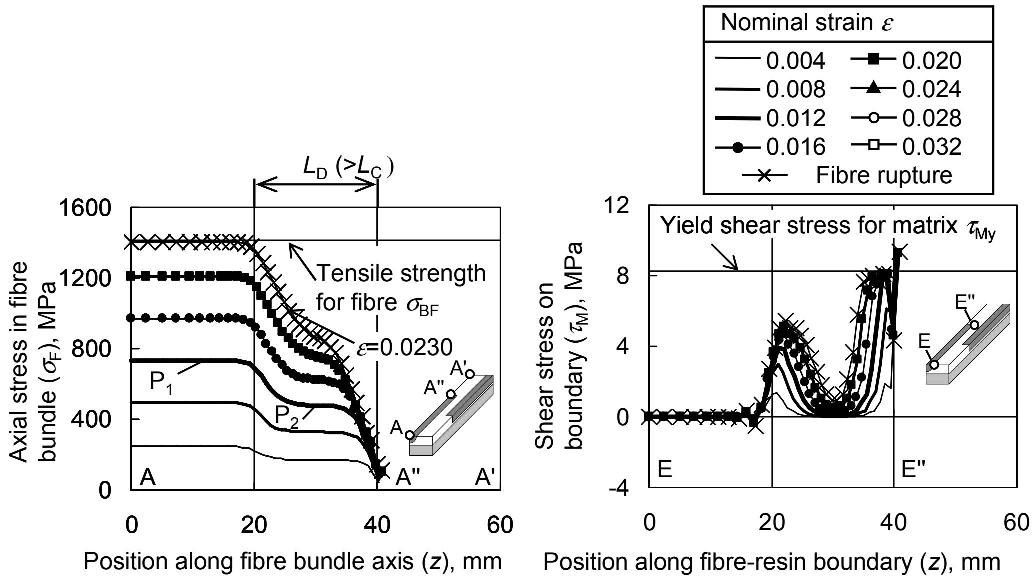


Figure 4: Stress distribution for Case (1)

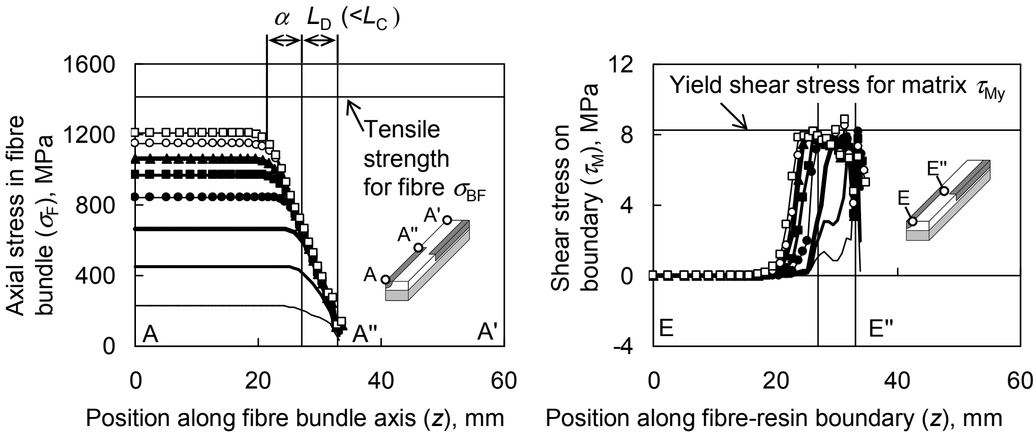
Figure 5(a) shows the result for Case (2) where fibre bundles, supplied from two directions, are sandwiched by two metal plates, and the overlap length L_D is longer than critical length L_C. The shear-stress field is confined within the overlapped part L_D. Axial stress σ_F of the fibre bundle has two plateaus, P_1 and P_2, and two slopes following equation (1). As the plates also play a role of supporting tensile load, the stress proportion is not simple and the axial stress at the overlapped part P_2 is larger than half of the axial stress at P_1. As a result, shear stress τ_M is larger around z =40 mm than around z =20 mm.

Figure 5(b) shows the result for Case (2) when the overlap length L_D is shorter than critical length L_C. It is noteworthy that the shear-stress field expands beyond the overlapped part L_D. Even in the single-way-bundle part, axial stress continues to increase in the left-side direction in the area denoted by α. It is thought that the supporting plates have a role to convey stress to the single-way-bundle part. The existence of surplus length α is the reason why FML can reduce the minimum bare overlap length L_{DN} for maintaining tensile strength less than L_C calculated by equation (2).

Based on the numerical study above, the role of the overlap part was clarified. Shear stress τ_M on the boundary changes corresponding to axial stress σ_F of the fibre bundle which should be 0 at the tip of the bundle and should be a certain constant value in single-way-bundle part P_1. Due to this stress distribution, the whole laminate can withstand the applied load, even if the fibre bundles are not continuous. The relationship between shear stress and axial stress should comply with equation (1). When the plate does not exist, the overlapped part L_D should be longer than critical length L_C, which is calculated by equation (2) in order to maintain strength of the laminate as high as the value predicted by the law of mixture [16]. However, the supporting plate would reduce the needed length for the maintenance of strength by surplus length α in Fig. 5(b). Surplus length α would change depending on the mechanical properties and thickness of the plates.



(a) Overlap length L_D=20mm



(b) Overlap length L_D= 6mm

Figure 5: Stress distribution for Case (2)

4 EXPERIMENTAL RESULTS

4.1 Effect of temperature in 2nd stage of deformation

According to equation (1), when yield shear stress τ_{My}, which is the maximum value of τ_y, is enough low, axial stress σ_F would not be increased as the deformation will not conveyed between fibre bundles. This situation is easily realized by heating FML because the matrix is a thermoplastic resin, which melts completely over 100 degrees Celsius [17]. The effect of temperature on the formability of FML of case (2) is tested using device in **Fig. 6.** 4 rod heaters were used for heating FML. After the temperature at the surface of FML reached a saturated value, the temperature was recorded as heating temperature T. The experimental result is shown in **Fig. 7** in the form of stress-strain diagram with overlap length L_D of 30 mm. Overlap L_D of 30 mm is much longer than critical value L_C calculated equation (1) for room temperature.

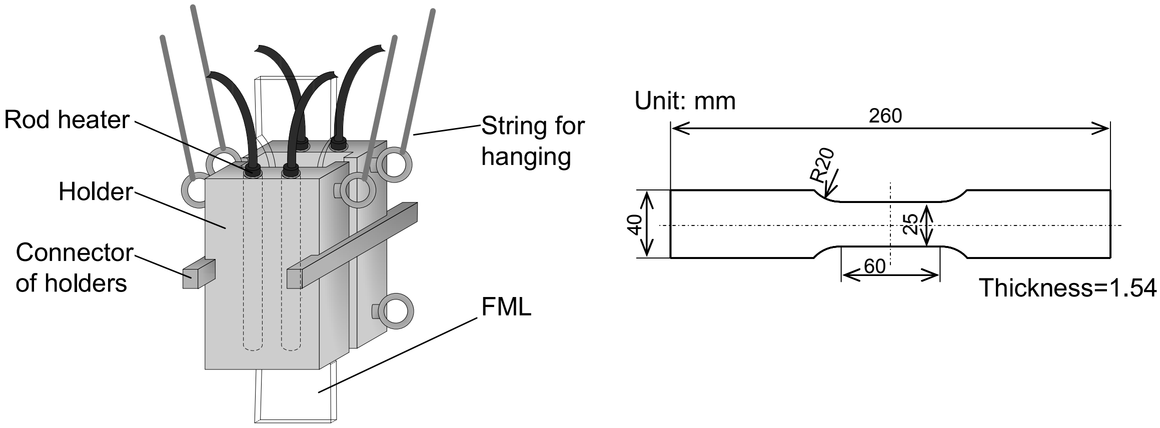


Figure 6: Schematic illustration of heating device and geometry of FML for tension test

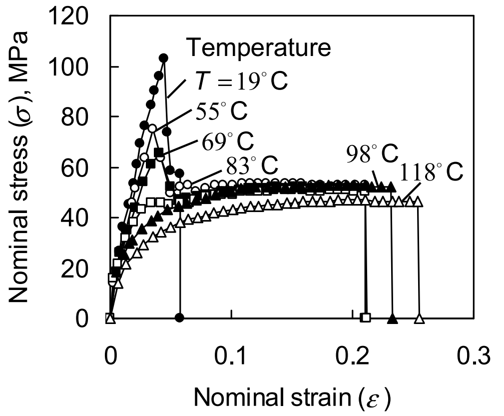


Figure 7: Effect of temperature on Stress-strain diagram for Case (2) with overlap length of 30 mm at 2nd stage of heating temperature

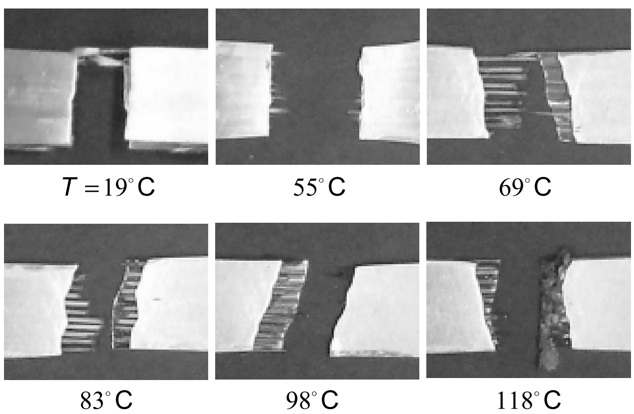


Figure 8: Effect of heating temperature on fracture mode of FML at 2nd stage

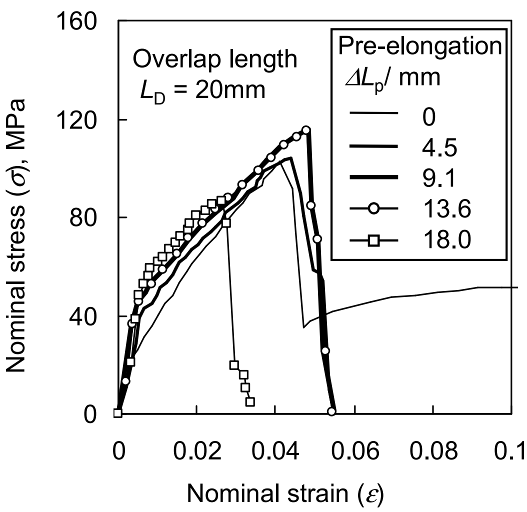
When the heating temperature T is at room temperature, the thermoplastic resin conveyed shear stress completely, the fibre bundles are tightly elongated so that tensile strength reached over 100 MPa and suddenly dropped due to rupture at the fibre bundles. With increase of heating temperature T, tensile strength decreased and total elongation increases. When the heating temperature is over 80 degrees, as the thermoplastic soften satisfactory, FML elongated more than 0.2 at nominal strain.

Figure 8 shows effect of heating temperature on fracture mode of FML at the 2nd stage of deformation. When the heating temperature T is lower than 60 degrees Celsius, the thermoplastic resin conveyed shear stress to fibre bundles, rupture occurred at the fibre bundles. On the other hand. The temperature T is over 60 degrees Celsius, the thermoplastic resin could not convey shear stress to the fibre bundles, and the bundles were pulled out from the resin.

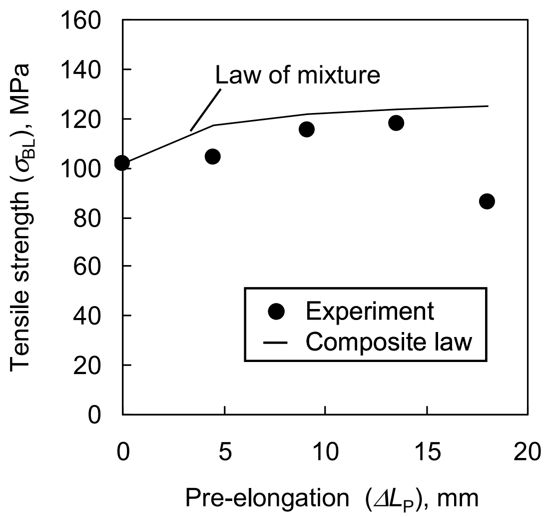
4.2 Effect of overlap length on strength at 3rd stage

In order to verify the function of the proposed FML, Case (2), experiments were carried out by a strategy as explained in Fig. 1, which is composed of three stages, i.e. (1st stage) lamination, (2nd stage) forming under a heated condition and (3rd stage) tension test at room temperature. The geometry of test piece was the same as that shown in Fig. 6. Overlap length L_D was fixed at 20 mm.

At the 1st stage, FML was laminated at a temperature of 120℃, which melts the thermoplastic resin. At the 2nd stage, FML was elongated at a constant temperature of 120℃, after being re-heated by a heater which was mounted to the tension test machine as shown in Fig. 6. At the 3rd stage, FML was elongated again at room temperature and the stress-strain relationship was measured. Pre-elongation ΔL_p at the 2nd stage ranges from 0 to 18 mm against overlap length L_D of 20 mm.



(a) Stress-strain diagram



(b) Tensile strength

Figure 9: Effect of pre-elongation on mechanical properties of FML at 3rd stage of room temperature

According to the FEA result, which is not shown in the authors' previous paper [14], as the minimum bare length L_{DN} of the overlapped length should be around 8 mm, pre-elongation ΔL_p could be up to 12 mm (=20 - 8) while maintaining tensile strength. **Figure 9**(a) shows the effect of pre-elongation at the 2nd stage for a stress-strain diagram at the 3rd stage. Regardless of pre-elongation, stress increases with increase of strain and abruptly drops at some strain value. **Figure 9**(b) shows the effect of pre-elongation ΔL_p on tensile strength σ_{BL} of FML. With increase of pre-elongation ΔL_p, tensile strength σ_{BL} increases according to the law of mixture [16], up to ΔL_p =13.6 mm, which is almost equal to, but a little bit longer than predicted by FEA.

Judging from the result of the tension test and observation of rupture, the FML with proposed structure has a funct ion of being able to be elongated up to 9.1 mm at the 2nd stage while maintaining sound tensile strength and bonding condition at the 3rd stage. This ability of elongation and formability is much higher than other FML structures.

5 CONCLUSIONS

- A structure for FML was introduced, which is composed of reinforcing fibre bundles, thermoplastic resin as the matrix and metal plates.
- The reinforcing fibre bundles are discontinuous, and are intentionally overlapped in the longitudinal direction. The resin including fibre bundles was sandwiched between the metal plates.
- FEA results show that when overlap length is appropriately long, the axial stress of the fibre bundle has a distribution with two slopes. This would provide tensile strength of FML as high as a composite of continuous fibre bundles which comply with the law of mixture.
- The rupture would occur at the single-way-bundle part.
- On the other hand, when overlap length is short, the shear strength reaches the yield value on the boundary through the whole overlapping area. Rupture would occur on the boundary.
- Experimental results showed when FML is heated at appropriate temperatures at the second stage of deformation, it would be elongated much longer than conventional composites.
- Experimental results also showed FML has as high tensile strength with sound bonding condition as expected even after pre-elongation up to 9.1 mm against the parallel part of 60 mm, which is much longer than other structures of FML.

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